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THE EFFECTS OF UNDERWATER EXPLOSIONS ON
SWIMBLADDER FISH

Ermine A. Christian

Naval Ordnance Laboratory
White Oak, Maryland

27 July 1973

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NAVAL ORDNANCE LABORATORY
WHITE OAK, SILVER SPRING, MARYLAND
EXPLOSIVES RESEARCH DEPARTMENT

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The Effects of Underwater Explosions on Swimbladder Fish

Underwater explosions are necessary components in various tests that must be performed during design and development phases of shock-hardened ships and new weapons. Recent legislation requires that the Navy consider possible adverse effects on the environment during the planning for such tests. A major factor in the environmental assessment is the amount of damage that might be inflicted on fish and other marine life in the vicinity of the explosion.

Fish that have gas-filled swimbladders are more vulnerable to explosions than many other forms of marine life, and most of the sport and commercially valuable fish are of this type. This study provides an improved capability to forecast the probability of harming such fish during underwater explosion tests. Hence, results presented here will be useful in estimating the environmental impact for a number of Navy programs.

This study is part of the pollution-abatement program of the Naval Ordnance Systems Command and was supported by Task ORD-0332-004/092-1/UF 554-301, "Environmental Effects of Explosive Testing."

The author is indebted to Dr. Andreas Rechnitzer for access to his unpublished data and analyses from his early work on fish vulnerability, and to Mrs. Verna K. Shuler and Mr. Joel B. Gaspin for the computations of theoretical cavitation zones.

ROBERT WILLIAMSON II
Captain, USN
Commander

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By direction

CONTENTS

	Page
I. INTRODUCTION.....	1
II. OBSERVED LETHAL RANGES.....	2
2.1 General.....	2
2.2 Observed Fish-Kill Ranges.....	2
2.2.1 Square-root of Charge Weight Damage Rule.....	2
2.2.2 Peak Pressure Damage Rule.....	2
2.2.3 Comparison of Lethal Damage Ranges.....	3
III. ADDITIONAL FACTORS THAT INFLUENCE LETHAL ZONE.....	5
3.1 General.....	5
3.2 Asymmetry of Damage Zone.....	5
3.3 Effect of Negative Pressure.....	6
IV. BULK CAVITATION FROM UNDERWATER EXPLOSIONS.....	7
4.1 General.....	7
4.2 Pressures in the Bulk Cavitation Zone.....	9
4.3 Boundaries of the Theoretical Bulk Cavitation Zone.....	13
V. CORRELATION OF BULK CAVITATION AND FISH DAMAGE ZONES.....	13
5.1 General.....	13
5.2 Damage Mechanisms.....	16
5.3 Variations Among Fish.....	16
5.4 Relative Susceptibility of Water and Fish Tissues.....	16
VI. ESTIMATES OF REMOTE DAMAGE ZONE.....	17
6.1 General.....	17
6.2 Dimensions of the Remote Damage Zone.....	19
6.3 Approximation Formulas for Shallow Charges.....	19
VII. COMPARISONS FOR SELECTED CHARGE CONFIGURATIONS.....	24
7.1 General.....	24
7.2 Comparison with Aplin (1947).....	24
7.3 Comparison with CBL (1948).....	25
7.4 Comparison with CEQ (1970).....	28
VIII. SUMMARY.....	28
REFERENCES.....	31
APPENDIX A.....	A-1

ILLUSTRATIONS

Figure	Title	Page
1	Previous Estimates of Fish-Kill Ranges vs Weight of Explosive Charge.....	4
2	Direct and Surface-Reflected Pressure Waves.....	8
3	Waveforms as Modified by Cavitation (Gaspin and Price, 1972).....	10
4	Pressure-Time Histories Within or Near Zone of Bulk Cavitation.....	12
5	Theoretical Bulk Cavitation Zones for Shallow 1-lb and 10-lb Charges.....	14
6	Theoretical Cavitation Zones for 1-Pound Charge at Various Depths..	15
7	Schematic of Damage Zones for Shallow and Deep Explosions.....	18
8	Theoretical Remote Lethal Zone Boundaries for 1-lb Charge at Various Depths.....	20
9	Theoretical Remote Lethal Zone Boundaries for 10-lb Charge at Various Depths.....	21

V

CONTENTS (continued)

ILLUSTRATIONS (continued)

Figure	Title	Page
10	Theoretical Remote Lethal Zone Boundaries for 100-lb Charge at Various Depths.....	22
11	Theoretical Remote Lethal Zone Boundaries for Charges at 100-ft Depth.....	23
12	Comparison of Data from Aplin (1947) with Predicted Remote Damage Zones for Swimbladder Fish in Deep Water.....	26
13	Comparison of Data from CBL (1948) with Predicted Remote Damage Zones for Swimbladder Fish in Deep Water.....	27
14	Comparison of Predicted Damage Ranges for a 2 Kiloton TNT Charge Detonated at 3000 ft Depth.....	29

THE EFFECTS OF UNDERWATER EXPLOSIONS ON SWIMBLADDER FISH

I. INTRODUCTION

1.1 A number of "fishermen" are familiar with the effects of underwater explosions on fish. Even a rather small charge of dynamite, if it lands near a school of fish, can go far towards filling the creel. The Navy has an antipodal interest in killing fish with explosives: the question is how to avoid a fish-kill with underwater explosions tests that must be carried out in ship-design and weapons-development tests.

1.2 The problem of reconciling the need for occasional underwater explosions tests with conservation of natural resources is not a new one. Long before public sensitivity to "environmental impact" reached today's high levels, military and commercial users of explosives were discussing this problem with conservationists. Since 1947 when a field test facility was established at Solomons, Maryland, for example, the Naval Ordnance Laboratory has continued to work closely with local agencies such as the Chesapeake Biological Laboratory and the Maryland Department of Chesapeake Bay Affairs to minimize the adverse effects of underwater weapons tests on fish and other marine life (e.g., NOL (1947), CBL (1948), Coker and Hollis (1950), Tiller and Coker (1955), Green and Davidson (1969))* . The effects of the explosions used in seismic surveys were studied in the early days of coastal oil explorations, and efforts to minimize fish kills have greatly influenced the types of sound sources used in such work (e.g., Aplin (1947), Hubbs and Rechnitzer (1952), Fitch and Young (1948), Gownlach (1944), Jakosky and Jakosky (1956), Hubbs et al (1960)).

1.3 Not only specialized groups such as those noted above, but also significant segments of the general public have frequently been concerned about the real or imagined adverse effects of explosions on marine life. Any period of poor catches by commercial or sports fishermen, or the appearance of dead fish which occasionally wash ashore in quantity, are likely to be attributed to explosions if there have been any within miles of the spot. Even undetonated explosives may be suspect. For instance, shortly after World War I a catastrophic mortality among oysters all the way from Southern Italy to Northern Ireland was rumored to be the result of surplus TNT and other explosives that had been dumped off the mouths of rivers. (Investigators at the Marine Biological Association in Plymouth, England, found that, in fact, the explosives did not appear to have any effect on oysters even when lumps of the material were added to laboratory oyster tanks and to cages of shellfish in an estuary, Schlee (1970).)

1.4 Despite this long-standing and broad interest in the subject, not too much progress has been made towards defining zones of fish lethality for an underwater explosion. The majority of the numerous references on the subject give only qualitative observations. The occasional reports of controlled tests against caged specimens do not provide damage criteria from which lethality ranges for other charge configurations can be predicted.

* References on page 31.

1.5 A capability to predict explosion lethality zones is of special interest for one particular category of marine life, viz., fish that have gas-filled swimbladders. This category includes most of the sport and commercially valuable fish, and swimbladder fish are far more vulnerable to explosions than bottom fish or shellfish. Consequently, the present study is aimed at that most pressing problem.

1.6 This study describes a proposed new method of predicting lethal zones for swimbladder fish. Although it has not yet been tested experimentally, the proposed new damage model promises to be an improvement over previous attempts to correlate parameters of the explosion pressure field with observed lethal ranges.

II. OBSERVED LETHAL RANGES

2.1 General

At the outset of this study, an effort was made to reduce available lethality data to a common basis for comparison. One published study, that of Lavergne (1970), contains a general damage rule in which lethal range is directly proportional to the square root of the explosive charge weight. For the most part, however, previous attempts to define lethality in terms of explosion parameters have been based on some maximum allowable value of p_{max} , the maximum pressure of the shock wave generated by the explosion. The lethal ranges predicted by these two damage criteria are compared with observed fish-kill data below.

2.2 Observed Fish-Kill Ranges

2.2.1 Square-root of Charge Weight Damage Rule

For explosive charges weighing between about 4 and 120 pounds, Lavergne (1970) gives the following relationship between lethal range, R_L in feet, and charge weight, W in pounds:

$$R_L = 2.2 \cdot K \cdot W^{1/2}. \quad (1)$$

Here the coefficient K depends upon the species of fish and varies from a value of 12 for carp to a value of 54 for other types of fish. Apparently Lavergne has additional data to supplement the value of $K = 12$ for carp, which is the only value given by Lovlia et al (1966).

2.2.2 Peak Pressure Damage Rule

Not surprisingly, the explosion effect most frequently mentioned in connection with fish kill is the initial very high pressure at the front of the shock pulse, p_{max} . For most high explosive charges the amplitude of this peak pressure at a particular range R is related to a charge of weight W by an equation of the form

$$p_{max} = k (W^{1/3}/R)^{1.13}. \quad (2)$$

Here the proportionality constant, k , depends upon the explosive material.

For purposes of the present comparison we can use the well-known TNT peak pressure equation given by Arons (1954), since typical variations in P_{max} for different high explosive materials are minor compared to the variability in reported fish kills with such charges. With the units of pressure in psi, charge weight in lb, and range in ft, $k = 2.16 \times 10^4$ for TNT. Thus, if some particular peak pressure, P_L (psi), is taken as the criterion for lethality, we can write the corresponding equation for lethal range, $R_{L,p}$ (ft), in terms of charge weight W (lb):

$$R_{L,p} = C \cdot W^{1/3} \quad (3)$$

where

$$C = 6852 \cdot P_L^{-0.885} \quad (4)$$

From their studies with dynamite charges weighing 1 to 10 lb, Hubbs and Rechnitzer (1952) suggested values of $P_L = 40$ to 70 psi for the onset of lethality, which would give a value of C in Equation 3 ranging from about 262 to 160. The rough estimates of 70 psi for onset and 180 psi for certain lethality given by NOL (1947) give corresponding values for C of 160 (onset) and 69 (certain lethality).

2.2.3 Comparison of Lethal Damage Ranges

2.2.3.1 It is apparent from Equations (1) and (3) that ranges of fish mortality predicted for certain weights of explosives can differ by almost an order of magnitude. This wide choice of predicted lethal ranges is illustrated in Figure 1 where R_L from Equation (1) and $R_{L,p}$ from Equation (3) are plotted vs charge weight. The two dashed curves show the $W^{1/2}$ function of Equation (1) for the extreme K values of 12 and 54; the three solid curves show the $W^{1/3}$ function of Equation (3) for the above-noted critical pressure levels of 40, 70, and 180 psi.

2.2.3.2 Also shown on Figure 1 is a rather confusing assortment of fish-kill observations that have been reported in terms of specific charge weights and ranges. These include:

(a) the Chesapeake Biological Laboratory data (CBL, 1948) that give an outer limit of lethality at 500 ft and cover the measurement ranges from 200 ft outward with charge weights of 30 to 300 lbs;

(b) the semi-qualitative observations of Coker and Hollis (1950) who concluded, from the numbers of free-swimming fish killed by a series of explosions tests with 250 to 1200 lb charges in Chesapeake Bay, that the radius of fish kill appeared to fall between 300 and 600 ft, regardless of charge size;

(c) the limited experiments of Gowanlock (1947) showing that for charge weights between 300 and 800 pounds the lethal range remained constant at something like 200 ft;

(d) and, finally, the limited studies of Aplin (1947) who found lethal ranges of 250 ft from a 40-lb charge for small (1/2 to 3/4-lb) spotfin croakers.

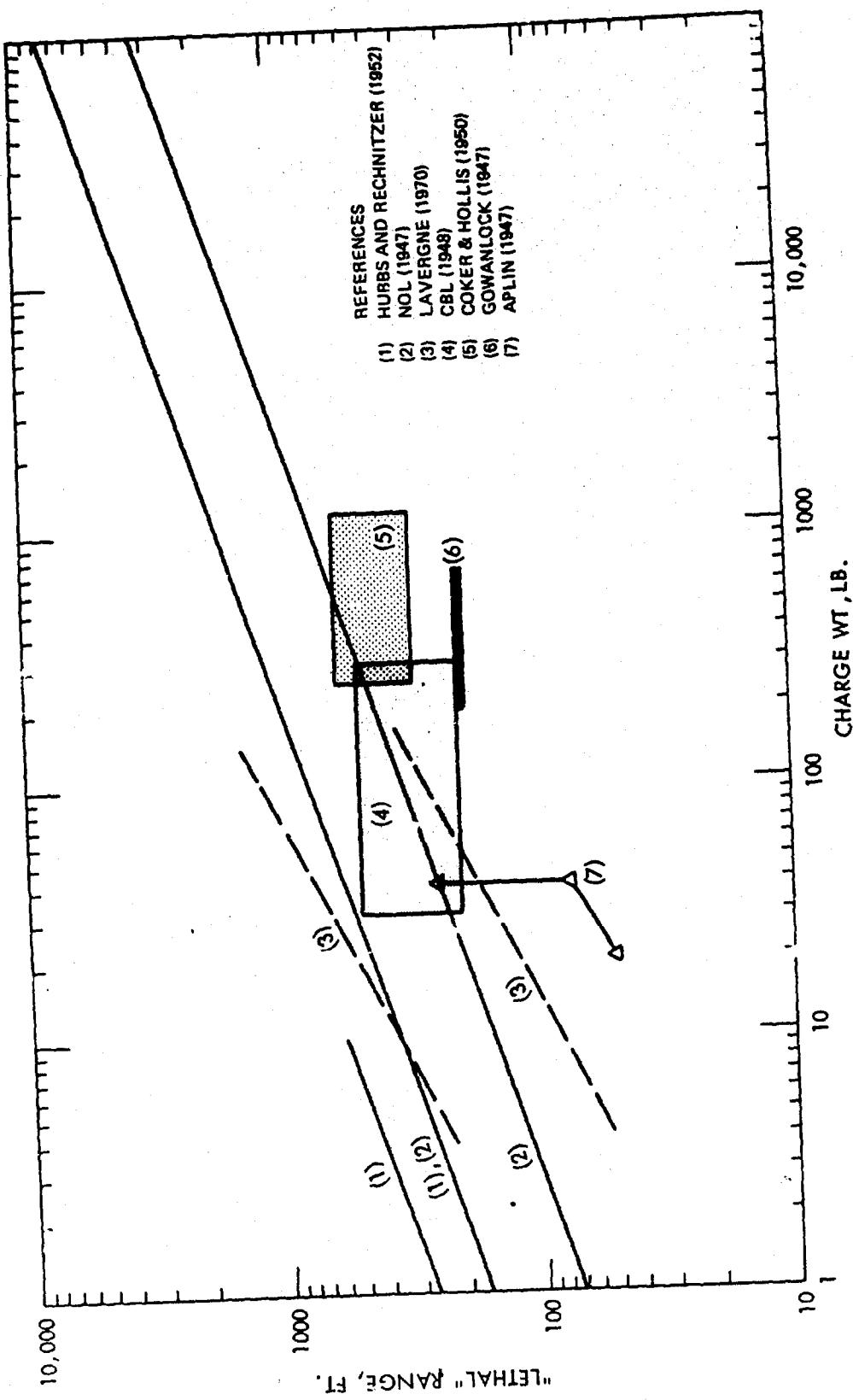


FIG. 1 PREVIOUS ESTIMATES OF FISH-KILL RANGES VS. WEIGHT OF EXPLOSIVE CHARGE

(Roncador sternsi) and kingfish (Genyonemus lineatus), 75 ft from a 40-lb charge for larger (1-1/2 to 2-lb) croakers and white seabass (Cynoscion nobilis), and 50 ft from a 20-lb charge for opal-eye perch (Girella Nigricans). (These latter two positions correspond to peak pressures of some 700 to 800 psi.)

2.2.3.3 An additional set of data which is not shown on the graph of Figure 1 because it falls outside the range of variables adds even further confusion to the picture. Tyler (1960) found a dramatic increase in lethal range as water depth increased. Using half sticks of dynamite--which are roughly equivalent to 1/4 pounds of TNT--placed directly on the bottom, he found that the lethal ranges for caged salmon within several inches of the bottom increased rapidly from 3 ft to about 16 ft as the water depth increased from 2 ft to 6 ft.

2.2.4 Certainly one would expect to find an appreciable amount of scatter among the results of studies as diverse as those represented by Figure 1. For example, neither the Hubbs and Rechnitzer nor the CBL studies--which comprise the only extensive, controlled, well-documented test series cited--were performed with simple free-water charge configurations matching the p_{max} computations*.

Nevertheless, even allowing for experimental scatter, the compilation of Figure 1 should show some common trends if the general damage rule were a simple function of charge weight. In fact, however, from Figure 1 the observed lethal range appears to vary very little with increasing charge weight. This unexpected behavior, combined with other factors discussed in the following sections, points to the need for a more sophisticated explosion input to the damage model than functions such as Equations (1) and (3).

III. ADDITIONAL FACTORS THAT INFLUENCE LETHAL ZONE

3.1 General. In both of the lethal range expressions discussed above, the only explosion parameter used is the weight of the charge. This functional form of the damage equation implies that (a) the fish-kill zone is symmetric in all directions about the charge, and (b) the damage is related directly to the compressional wave sent out by the explosion. This probably is the case very close to the charge, where fish would be completely destroyed or badly mutilated by the blast. Frequently, however, fish killed at greater ranges from an underwater explosion have no visible exterior damage and have viscera that are essentially intact except for a ruptured swimbladder. Since we would like to be able to predict the maximum probable fish kill from any given explosion, it is this latter type of damage that we wish to correlate with parameters of the explosion pressure field. The outer limits of the zone for swimbladder rupture are neither symmetric about the charge nor defined by the compressional wave alone.

3.2 Asymmetry of Damage Zone. Fish at some depth in the water are apparently less vulnerable to an explosion than fish near the water surface. Coker and Hollis (1950), observing some explosions in the Chesapeake Bay, suggested that the shots may have killed only those free-swimming fish that happened to be in the upper

* Hubbs and Rechnitzer (1952) were using so-called "jetted charges," as discussed in Appendix A. The Chesapeake Biological Laboratory tests were in relatively shallow water; the peak pressure from the shock wave probably does conform to the free water equation that is used here, but at greater ranges there is clear evidence in terms of the fish mortality that secondary pressure pulses were present so that the total pressure time histories do not match those of free-water shots.

strata of the water at the time of the shots. Tiller and Coker (1955) noted that the heaviest mortalities observed from a number of explosion tests occurred rather consistently in species which typically live and feed at or near the surface, or which move frequently into the middle or upper layers of the water. The data of Hubbs and Rechnitzer (1952), when treated in the manner of Appendix A to this report, show that near-surface fish were killed by pressure waves of lower amplitude than the near-bottom fish.

3.3 Effect of Negative Pressure

3.3.1 The observation that fish kills seem to be greater at shallow than at deep depths provides a valuable clue as to which portions of the explosion pressure field are most damaging. As discussed later in Section 4, the compression wave generated by an underwater explosion is reflected back into the water as a tension wave. Apparently, living tissue of all kinds is readily damaged by negative pressure (Ward et al., 1948). Swimbladder fish are especially sensitive to tension inasmuch as they contain a sizeable air sac which is highly vulnerable to overextension.

3.3.2 During the normal vertical migrations of deep-water fish, the swimbladder, which has an essentially constant volume, can adjust to surprisingly large and rapid changes in hydrostatic pressure. The sophisticated gas-exchange mechanisms associated with this hydrostatic organ in various fish species are discussed by Marshall (1960). Some idea of the pressure gradients that can be accommodated might be drawn from observations of the so-called "deep scattering layer" which is often found in open ocean areas. The population of this reflective "layer" of biologicals varies from place to place, but in many cases it is thought to be masses of swimbladder fish which rise to feed near the surface at night and return to depth at sunrise. Clarke and Backus (1956) measured an upward migration of about 1000 ft for the scattering layer, and during the period of most rapid movement the hydrostatic pressure decreased at the rate of some 4 psi per minute. Similarly, Hersey et al (1962) showed deep scattering layers moving upward at various speeds corresponding to decompression rates as high as about 5 or 6 psi per minute. These migration rates indicate a remarkable biological ability to accommodate decreases in pressure.

3.3.3 Although swimbladders may be able to adjust naturally to rather large pressure gradients, when man introduces unnatural stresses the system is easily disrupted. For example, the bladder will be overexpanded and possibly burst if the fish is hauled rapidly to the surface. Marshall (1960), in his discussion of injured swimbladders among fish caught in trawls, noted that 45 percent of the cod taken at 20 fathom depths, and all of the cod taken at 30 fathoms or deeper, arrived at the surface with ruptured swimbladders. The fact that swimbladders are distended when fish are brought up rapidly enabled Kanwisher and Ebling (1957) to select as their "deep" specimens those fish which floated when emptied from the trawl into a bucket of water on board ship.

3.3.4 A very modest tension, when directly applied in laboratory tests, is also sufficient to injure the swimbladders of some species. Hubbs and Rechnitzer (1952) found that negative pressures of only one atmosphere (14.7 psi) or less quickly killed marine fish, and mention similar experiences with fresh water fish. Brown (1939) showed that the guppy could not successfully adapt to decompressions of more than about one-half an atmosphere. Hogan (1941) applied

negative pressures of up to one atmosphere to a variety of fish, for periods of 10 to 30 seconds; he found that physostomous fish (which have an "open" swimbladder connected to the alimentary canal) were often able to withstand the pressure drop, but that physoclistous fish (which have "closed" swimbladders) suffered hemorrhage in the circulatory system and often died. Young salmon that were tested by Muir (1959) could usually survive decompressions of about one atmosphere; but when the pressure was lowered to the vapor pressure so that the water cavitated, mortality was high. In contrast to these injuries caused by negative pressures, no ill-effects resulted when Rowley (1955) subjected rainbow trout to positive pressures of more than 13 atmospheres.

3.3.5 Apparently the swimbladder literally explodes when a fish is within the lethal zone of an underwater explosion. Ruptured swimbladders examined in CBL (1948) tests always showed the edges of holes turned outward, and debris from broken blood vessels blown into the abdominal cavity. The only external signs of injury found by Tyler (1960) was the disappearance of a small patch of scales from each side of the fish in the vicinity of the swimbladder, which one can conjecture resulted from a sudden overextension of the bladder. Rechnitzer (1971) observed evisceration of fish exposed to explosions, a condition that is difficult to ascribe to a compression wave.

3.3.6 The above observations provide ample evidence that swimbladder fish are easily injured by negative pressures. Furthermore the types of injuries inflicted by underwater explosions appear to be the results of tension, rather than compression, forces. This suggests a relationship between bulk cavitation--in which process the water itself is "torn apart" by the surface-reflected shock wave--and explosion damage to swimbladder fish. In the following discussion we will first describe the zone of bulk cavitation associated with an explosion, and then suggest a plausible damage model based on this phenomenon.

IV. BULK CAVITATION FROM UNDERWATER EXPLOSIONS

4.1 General

4.1.1 As noted earlier, a typical underwater explosion generates a spherical shock wave. The peak pressure at the front of the outgoing wave decreases with increasing range as shown in Equation (2). The pressure behind the front decays exponentially for a time, and then more slowly in the later portions of the wave. When the shock wave hits the air-water interface at the surface, a tension wave, the inverted image of the outgoing compression wave, is reflected back down into the water. Thus, as shown in the sketch of Figure 2, the pressure wave at a particular point in the water is a combination of the compression wave coming directly from the charge and the surface-reflected wave that arrives a little later. The actual waveform observed at the point A in Figure 2 depends upon geometry: the depth of the point and its distance out from the charge, and the depth of the charge itself, all influence the time separation and relative amplitudes of the two interacting waves*.

4.1.2 If the compression wave is still of moderately high amplitude when it reaches the surface, then the above picture of a simple reflected tension wave is not correct. Water cannot support very much tension. When the negative

* Shuler (1968) gives a convenient computer program for determining the effects of surface reflections on the explosion pressure field.

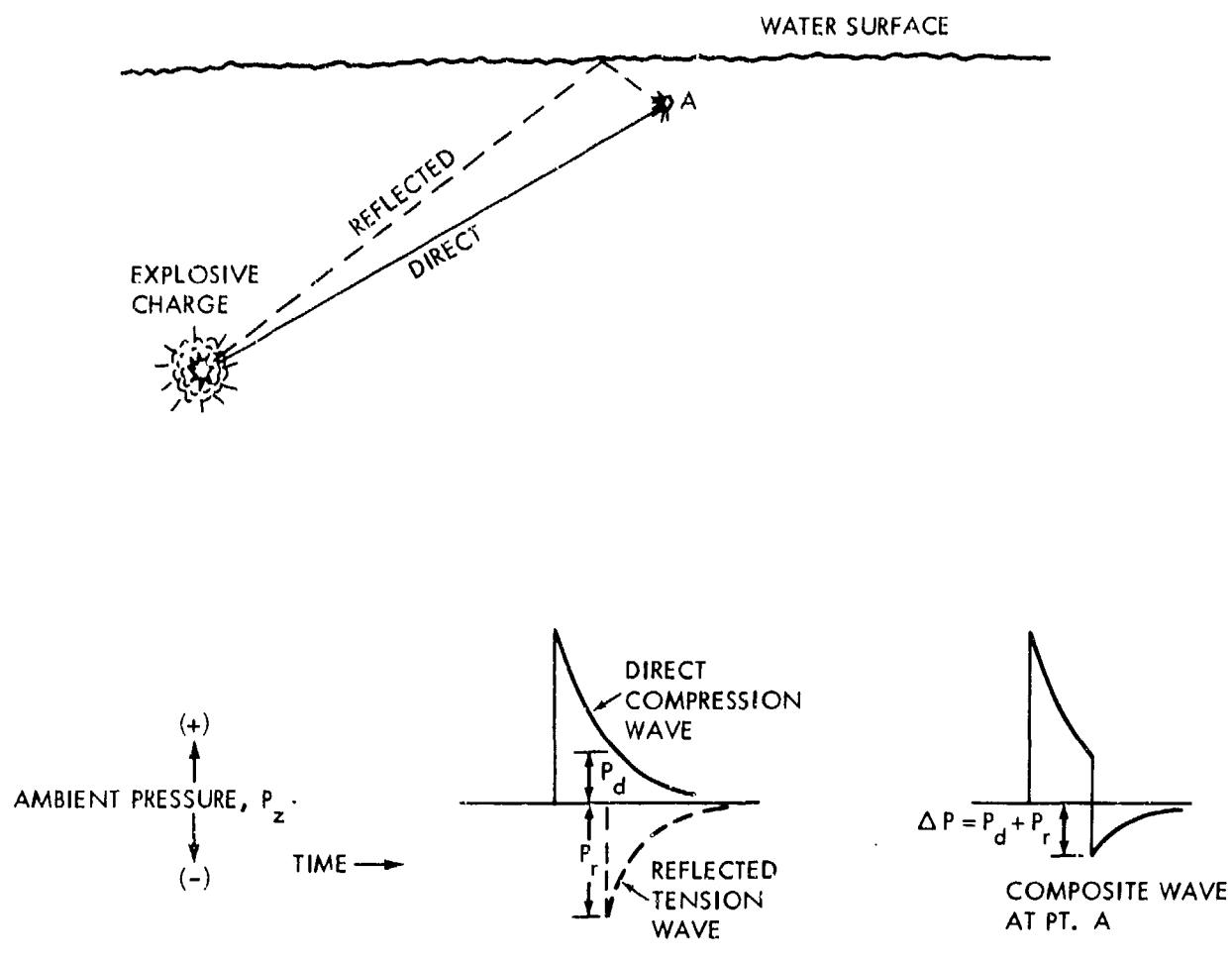


FIG. 2 DIRECT AND SURFACE-REFLECTED PRESSURE WAVES

pressure (ΔP) shown in the composite wave of Figure 2 is larger than some critical "breaking" pressure, the water is torn into many bubbles, i.e., it is cavitated. The cavitation, in turn, modifies the amplitude and duration of the tension wave. Since we are trying to correlate fish mortality with the negative pressures resulting from an explosion, we need a method of estimating both realistic pressure values and the location of the cavitated region--the so-called "zone of bulk cavitation"--for various weights and depths of explosion charge.

4.1.3 The phenomenon of bulk cavitation has been the subject of numerous studies since it was first described by Kennard (1943) but, unfortunately, very little of the theoretical and virtually none of the experimental effort has been directed towards defining the negative pressures that are of interest here. Consequently, Gaspin and Price (1972) recently re-examined the implications of bulk cavitation for this application; much of the following discussion is based on their study.

4.2 Pressures in the Bulk Cavitation Zone

4.2.1 The critical quantity in cavitation is tension. To predict whether or not a particular explosion will give rise to cavitation we need to know both the "breaking" pressure, or cavitation pressure (P_c), of the water and the likelihood that the explosion pressure wave will attain this value. At the present time we have very little experimental information on either of these scores, and must depend heavily on theory.

4.2.2 Various values of P_c have been measured or deduced from related phenomena: Couzens and Trevena (1969) measured 8.5 atmospheres for ordinary tap water and 15 atmospheres for boiled deionized water. Weston (1960) estimated approximately 20 atmospheres based on visible surface corrugations above small explosions; and values as high as 400 atmospheres have been deduced from photographs of the spray dome thrown up by explosions. But actual pressure measurements of explosions in the ocean indicate that $P_c = 0$ is a reasonable assumption for practical purposes (Coles (1942), Arons et al (1949), Wentzell et al (1969)).

4.2.3 With the pressure notation shown in Figure 2, the theoretical development of Arons et al (1949), which Gaspin and Price (1972) followed, says that cavitation will occur when

$$P_d + P_r + P_z = P_c = 0 \quad (5)$$

In other words, there will be no cavitation unless the excess negative pressure ($P_d + P_r = \Delta P$) is at least as great as the hydrostatic pressure (P_z). By mapping the portions of the pressure field where these conditions obtain, Gaspin and Price outline the boundary of the cavitated region. Figure 3, which is from their report, shows idealized waveforms in the presence of cavitation.

4.2.4 The cross-hatched area at the top of Figure 3 is a two-dimensional section of the zone of bulk cavitation. The computational method adopted follows the common practice of treating the reflected wave as though it were generated by an image charge, as shown. Pressure waveforms at various points along one radial from the image charge are sketched on the lower half of Figure 3. The ambient

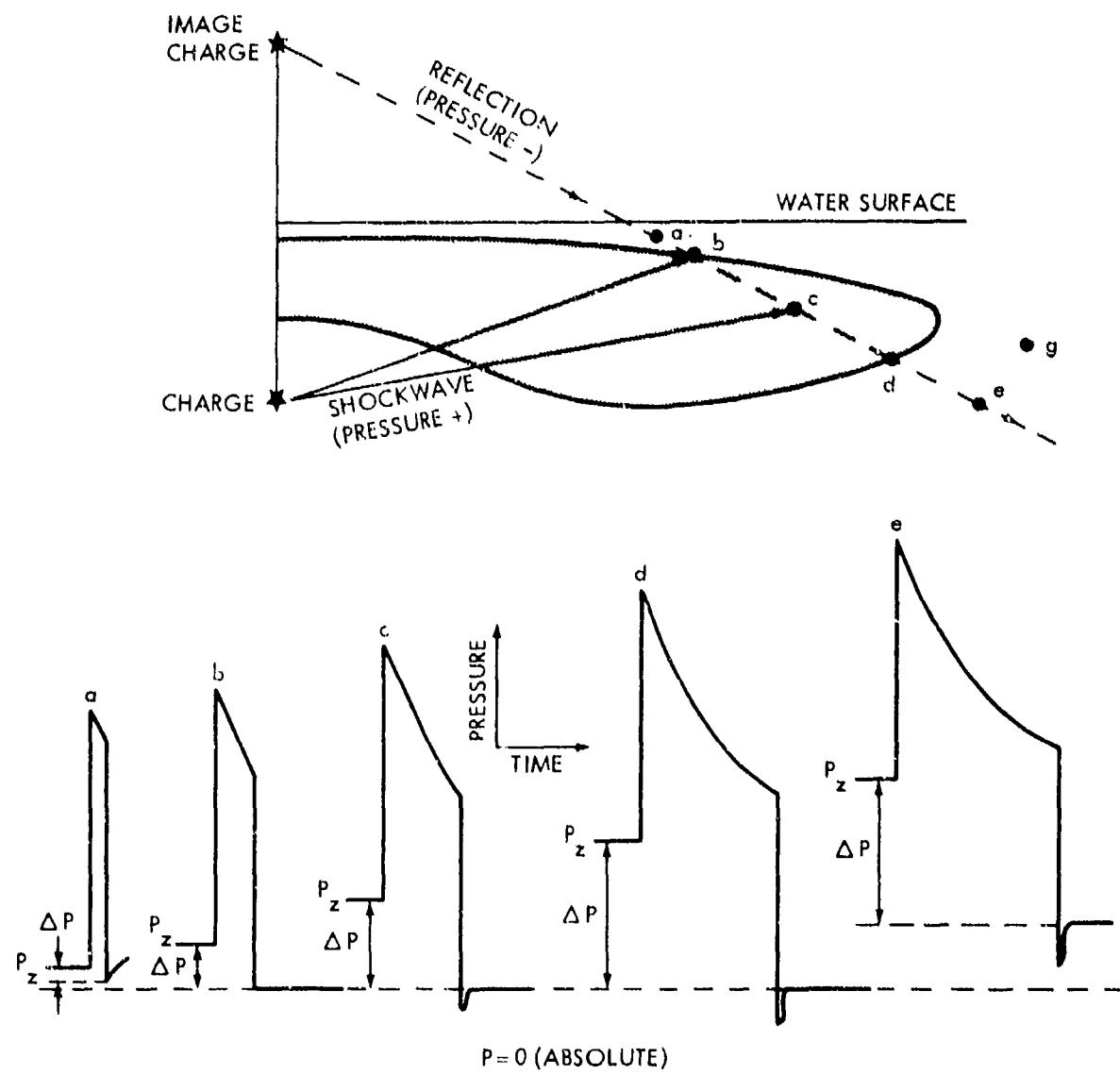


FIG. 3 WAVEFORMS AS MODIFIED BY CAVITATION (GASPIN AND PRICE, 1972)

(hydrostatic) pressure, P_z , increases as the points "a" through "e" become deeper.

Following the same sequence of points, the peak overpressure from the shock wave decreases slightly as radial distance from the charge increases, and the duration of the positive shock pulse increases as the reflected pulse arrives later. At point "a" the surface reflection lowers the pressure by an amount ΔP below ambient, but does not lower it as far as absolute zero so no cavitation occurs. At point "b", an upper boundary point, the reflected pressure is just sufficient to lower the total pressure to absolute zero. At points within the cavitation zone (point "c") and on its lower boundary (point "d"), the net tension is the limiting value of absolute zero. At points below the zone ("e"), the waveform retains the general features which characterize those at "c" and "d", but since the underpressure is less than hydrostatic the water does not cavitate. At the points within and below the cavitated region a hint of a sharp negative pressure spike is shown, to represent the finite time required for the water to cavitate. This spike is not always apparent on pressure-time recordings; to capture it faithfully one must have equipment with very good time resolution and high frequency response.

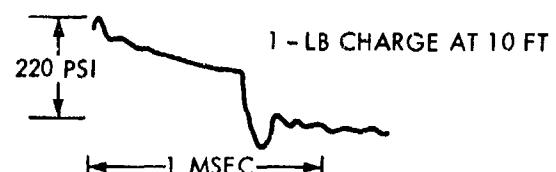
4.2.5 Tracings of some sample pressure time curves recorded in or near the cavitated region at a horizontal range of about 60 ft are shown in Figure 4. The top recording with the gage just below the surface at 1-ft depth was made by the Lovelace Foundation in their fresh-water pond (Lake Christian) in Albuquerque, New Mexico; the lower two records with the gage at 14-ft depth were obtained in the Potomac River near NOL's field station at Indian Head.

4.2.5.1 The Lovelace recording (Figure 4a), which was made in a small, quiescent body of fresh water, shows a negative pressure spike of about -70 psi at the front of the surface-reflected wave; the pressure then stabilizes at a level of about -20 psi. In the brackish river, however, (Figures 4b and 4c) we do not see an initial spike, only an essentially constant negative pressure of about -30 psi, i.e., about the same magnitude as the hydrostatic pressure at the 14 ft depth of the gage. All recordings were made using the same type of equipment, so these differences may represent the influence of the water purity.

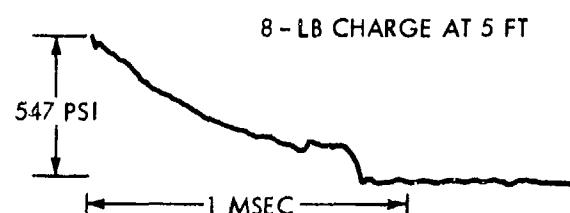
4.2.5.2 Note also that the later portions of the wave after the surface reflection arrives are essentially identical in Figures 4b and 4c. The positive pressure of the direct arrival is of the appropriately higher amplitude for the 8-lb charge than for the 1-lb charge. But once the wave is distorted by the cavitation phenomenon, it is the medium itself which controls the pressure amplitudes.

4.2.5.3 The very slight oscillations visible in the tail of the wave are probably real. Arons et al (1949) suggest that these small secondary pulses may be associated with the collapse of bubbles that are formed in or near the cavitation region.

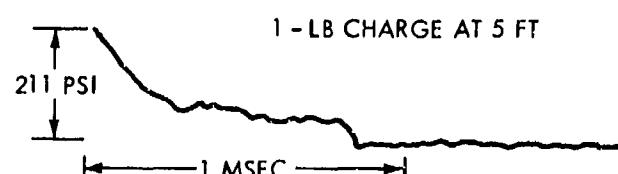
4.2.5.4 One would expect the pressure drop caused by the reflected wave to become somewhat less abrupt as the tension wave moves out along a radial from the image charge, traverses the cavitated region, and continues on down below the region (see Figure 3). Although this gradual decrease in the negative pressure gradient is not apparent in Figure 4, where all gages were at about the same distance from the charge, we have found evidence of such an effect among the fragmentary data examined.



a. GAGE NEAR SURFACE WITHIN ZONE
(RANGE \approx 60 FT, DEPTH = 1 FT)



b. GAGE DEEP WITHIN ZONE
(RANGE \approx 60 FT, DEPTH = 14 FT)



c. GAGE SLIGHTLY BELOW ZONE
(RANGE \approx 60 FT, DEPTH = 14 FT)

FIG. 4 PRESSURE - TIME HISTORIES WITHIN OR NEAR
ZONE OF BULK CAVITATION

4.2.6 Gaspin and Price suggest several possible methods of estimating the effective negative pressures below the cavitated region. They also point out the paucity of data for comparison with the theoretical results. In general, however, it seems reasonable to expect that (a) the largest negative pressures generated by an explosion will be found within or slightly below the cavitation zone and (b) their amplitudes will not greatly exceed the hydrostatic pressure at that depth (if we neglect the sharp initial spike). We will further show that these maximum tensions are probably no larger than a few atmospheres, since the cavitation zone does not extend down to very great depths below the surface.

4.3 Boundaries of the Theoretical Bulk Cavitation Zone

4.3.1 With the computer program developed by Gaspin and Price (1972), boundaries of the theoretical cavitation zones were estimated for a number of explosive charge weights and depths. Sample two-dimensional sections of such boundaries are shown in Figure 5, for 1-lb charges (5a) and 10-lb charges (5b). For each charge weight there are two curves, corresponding to charge depths of 1 ft and 5 ft.

4.3.2 Several interesting points about the extent of the bulk cavitation zone can be seen in Figure 5. Perhaps the most surprising fact is that increasing the charge weight by an order of magnitude does not increase the dimensions of the cavitated region as much as one might have expected: the maximum depth of the zone is approximately doubled, but the maximum horizontal extent is increased only by about 20 percent when charge weight is increased from 1 to 10 lbs. At the same time, merely lowering the charge from a 1-ft to a 5-ft depth more than triples the horizontal span of the cavitation zone, while leaving the depth unchanged.

4.3.3 This general pattern of increasing the horizontal span of the cavitation region by lowering the charge depth must, of course, be reversed at some point. With a very deep, small charge the pressure amplitudes at the surface will not be large enough to trigger the cavitation mechanism discussed above. The actual depth at which this occurs depends upon the size of the charge.

4.3.4 Figure 6 is an illustration of how the theoretical cavitated region first grows and then shrinks as a particular charge (1-lb in this case) is placed at greater and greater depth. Starting at the upper left, the sequence of sketches follows first down the left-hand column, then to the upper right and again down. Here the depth scale has been greatly exaggerated; Figure 6a, for example, is the same as the 1-lb, 1-ft curve of Figure 5a. For this charge weight the horizontal span of the cavitation zone continues to increase until the depth reaches about 200 ft, and then begins to shrink. The layer becomes very thin when the charge is deeper than about 50 ft. The last sketch, Figure 6e for a depth of 585 ft, is at the limit of resolution of the computer program. So we see that theory says there will be a layer of cavitated water, albeit a very thin one, even with the 1-lb charge hundreds of feet deep.

V. CORRELATION OF BULK CAVITATION AND FISH DAMAGE ZONES

5.1 General

There is patently a qualitative correlation between cavitated water and damaged fish swimbladders at certain locations within an explosion pressure field.

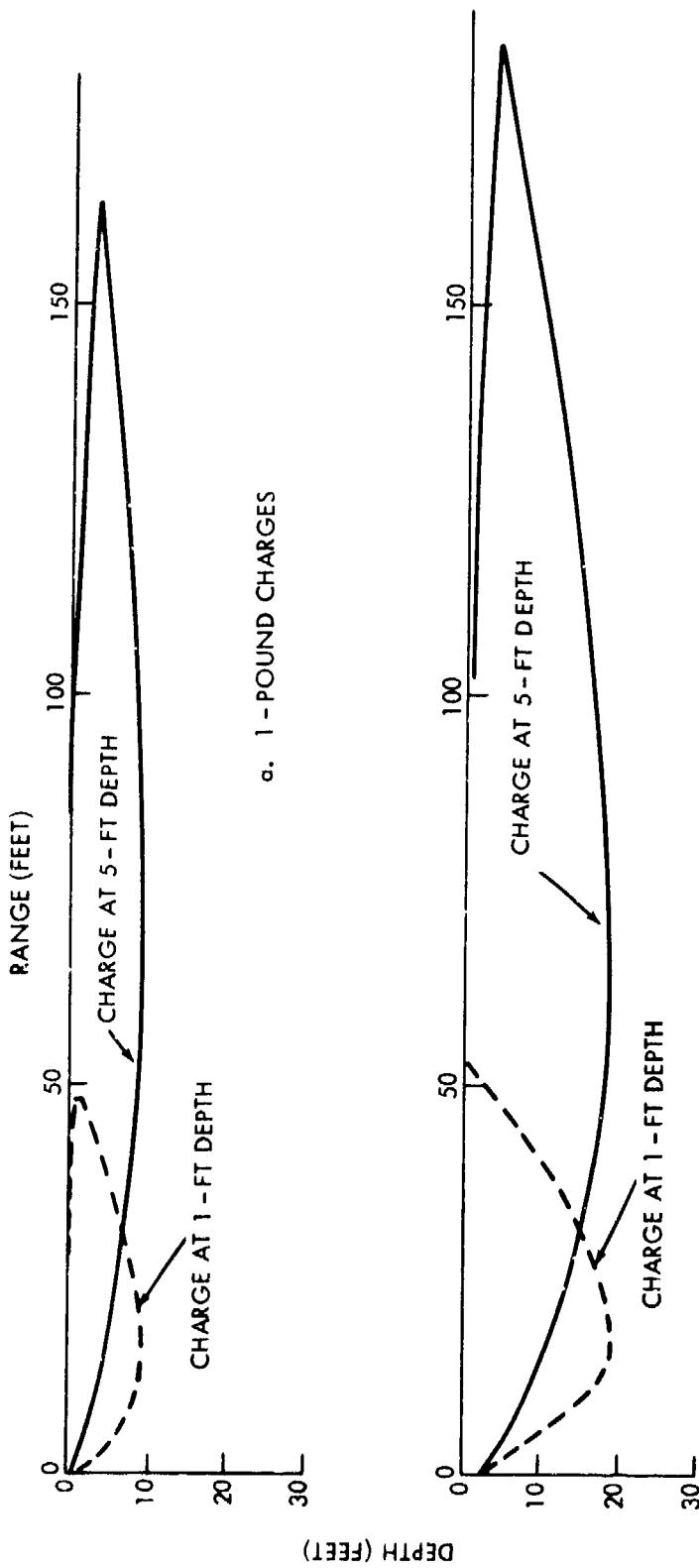


FIG. 5 THEORETICAL BULK CAVITATION ZONES FOR SHALLOW 1-LB AND 10-LB CHARGES

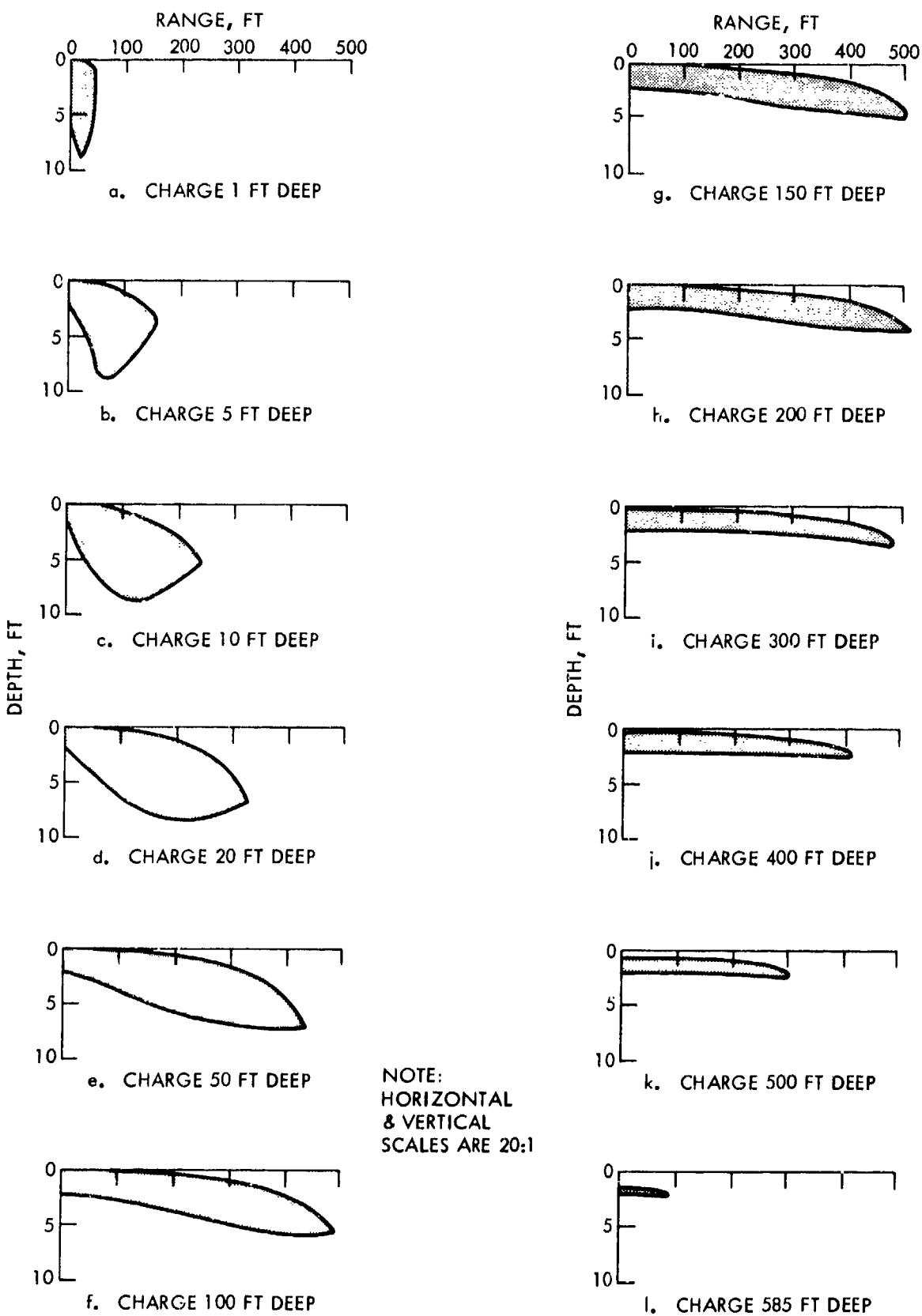


FIG. 6 THEORETICAL CAVITATION ZONES FOR 1 - POUND CHARGE AT VARIOUS DEPTHS

The question is whether we can arrive at quantitative relationships through which we can link damage response mechanisms and explosion parameters in a general damage prediction model.

5.2 Damage Mechanisms

5.2.1 The complex damage mechanisms involved when the swimbladder is ruptured by an underwater explosion are not clearly understood. The underwater acoustics literature contains a number of references dealing with the interactions between fish and low-amplitude, nondamaging pressure waves: e.g., Hersey and Backus (1966), Weston (1967), Love (1969 and 1971), Holliday (1972), Dang and Andrews (1971). These studies of how the fish interferes with the pressure waves do not provide direct information on how high-amplitude explosion waves interfere with the fish's vital organs.

5.2.2 The most pertinent document on damage mechanisms reviewed in the course of this study is the preliminary draft of an unpublished manuscript generously provided by Dr. Andreas Rechnitzer. Rechnitzer points out that the swimbladder will oscillate when it is struck by an explosion pressure wave, and that sufficiently energetic oscillations may give rise to shear strains and/or cavitation damage in the body tissues surrounding the bladder. This interesting and detailed theoretical study of the forces that must be taken into account provides valuable insight into the problem. In addition, however, Rechnitzer's paper also demonstrates the complexity of the problem, and notes that a number of measurements (e.g., damping rate of oscillation, stiffness and tension in the swimbladder wall) will have to be made before more quantitative treatments are possible.

5.3 Variations Among Fish

5.3.1 Although our interest is limited to fish that have gas-filled swimbladders, that general category contains a number of species. A study of the differences in their vulnerability to explosions is far beyond the scope of this report. Two fundamentally different types of swimbladder constructions should be mentioned, however: the "open" type which is connected to the alimentary canal by a duct (physostomous fish), and the "closed" type which have no such passageway (physoclistous fish). Intuitively, we would expect that at the outer limits of the lethal zone an "open" type of swimbladder might be more capable of adapting to the pressure changes than would the "closed" type, but that under more severe shock conditions the two types might suffer about equal damage. On the other hand, such differences in swimbladder construction may not matter in the explosion damage process since pressure changes occur within microseconds, too rapidly for the normal gas-exchange mechanisms to operate.

5.3.2 Additional factors that undoubtedly influence vulnerability are the age, size, and general state of health of the fish. There is some fragmentary evidence that larger fish are less vulnerable to explosion shocks than smaller ones, but this may not always be the case.

5.4 Relative Susceptibility of Water and Fish Tissues

5.4.1 Even without a detailed understanding of the biological factors and damage mechanisms, we can ask the question: if the water at some spot in an

explosion pressure field is torn apart by the tension wave, would a fish swimbladder at that same spot probably also be ruptured?

5.4.2 It is well-known that the amount of tension water can sustain without breaking apart is lowered if the water contains dissolved gas bubbles which act as cavitation nuclei (e.g., Eller, 1960). The density, bulk modulus of elasticity, and sound velocity are very nearly the same for fish tissue and for water (Andreeva, (1964), Lebedeva (1964)). Thus, if the swimbladder is equivalent to a sizeable air bubble floating in the water--an assumption that is reasonable insofar as its acoustic properties go--then the fish is probably more susceptible to disruption than the water itself. On the other hand, the swimbladder is surrounded by restraining tissues and bony skeletal structures which should offer some protection against overextension due to the tension. In short, with all the gaps in our knowledge at this time, we can almost equally well argue that the fish is more vulnerable or less vulnerable to cavitation than the water itself.

5.4.3 As a first approximation, we propose to assume that fish and water are equally vulnerable to cavitation. Certainly the negative pressure amplitudes and gradients associated with the bulk cavitation theory discussed above are comparable to those observed to be damaging to fish (Section 3). And for the most part, where we can draw any inferences from the literature, it appears that when fish were damaged by explosions they were probably also within or near the bulk cavitation zone. On balance then, this simple assumption that the zone of probable fish lethality coincides with the zone of bulk cavitation gives us a crude damage model that is plausible and seems to accommodate the available data. It may well be that such a crude model is adequate for most of our practical prediction needs: in typical underwater explosion field tests the local population may include various species of big fish and little fish, young and old, some ailing and some healthy. This first working model also has a distinct advantage in that it allows us to compare zones of probable fish lethality for different charge configurations without waiting for answers to all the biological response questions.

VI. ESTIMATES OF REMOTE DAMAGE ZONE

6.1 General

6.1.1 There are actually two fish damage zones associated with an underwater explosion as illustrated in Figure 7. As noted previously, fish very close to the explosion will be destroyed directly by the compression wave; the relatively small volume of water defined by this damage radius we have called the "immediate kill" zone. The much larger, near-surface damage zone which we are equating to the bulk cavitation region we have called the "remote damage zone." For a shallow explosion (Figure 7a), the two zones may overlap. For a deep explosion (Figure 7b), the two zones will probably be separated although there may be a damage region just above the charge (not shown in the sketch) connecting the two zones.

6.1.2 Functions of the type shown in Equations (1) and (3) would describe the near-charge "immediate kill" zone. Since we have no evidence that these particular equations represent test conditions free of surface effects (in fact, we know that the surface is a complication in Equation (3)), we are not recommending that they be used to estimate the "immediate kill" radius at this time.

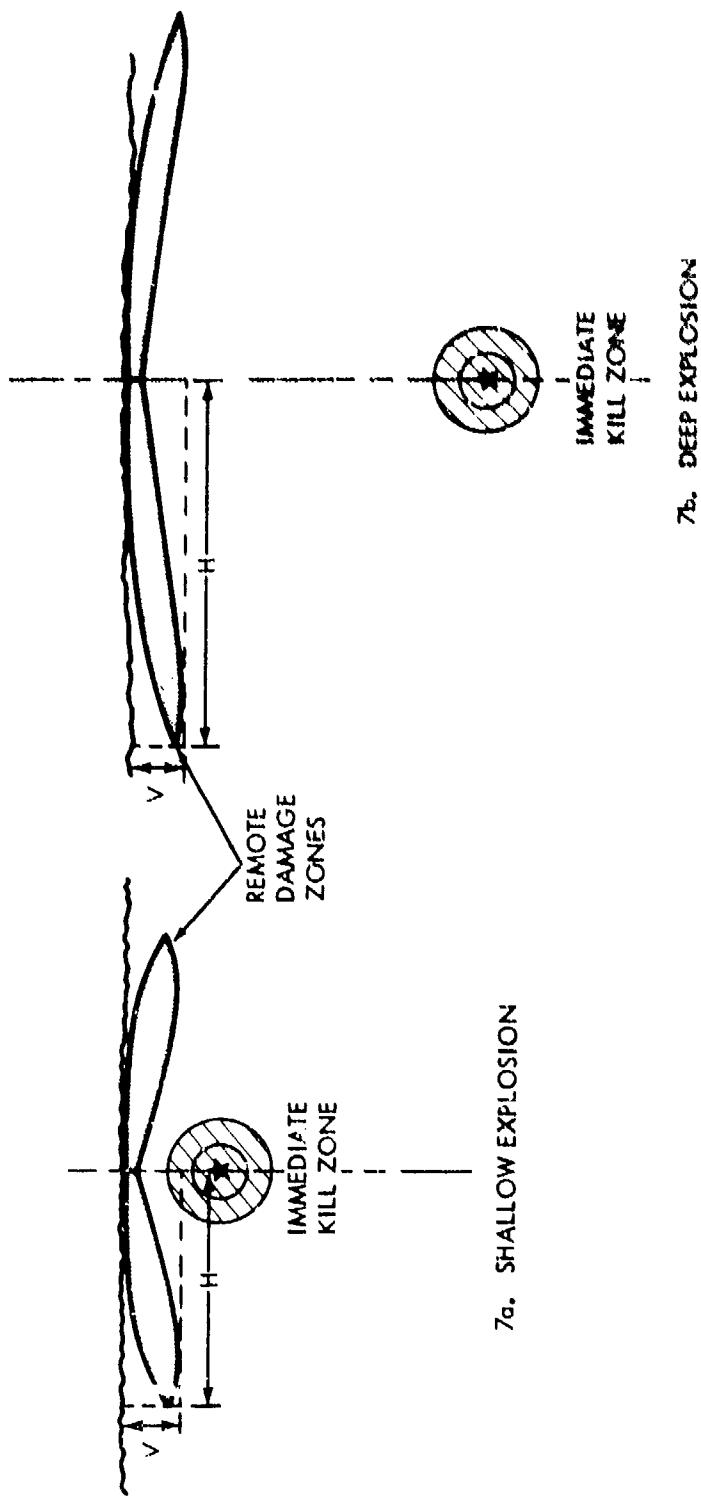


FIG. 7 SCHEMATIC OF DAMAGE ZONES FOR SHALLOW AND DEEP EXPLOSIONS

6.1.3 From available evidence, we believe that the remote damage zone is by far the larger of the two; also, it lies at shallow depth where the population of near-surface feeding fish is apt to be dense. Consequently, it seems reasonable to assume that the bulk of the fish damage caused by an explosion will occur in the remote damage zone.

6.2 Dimensions of the Remote Damage Zone

6.2.1 We are proposing to use the extremities of the bulk cavitation region to define the dimensions of the remote damage zone. In other words, we have boxed in the wing-shaped cavitation region (see Figure 7) with horizontal and vertical lines tangent to the boundaries, thus enclosing a disc of depth V and radius H , centered above the charge. We would expect the damage to be most severe near the center of this disc, and to taper off toward the outer limits where cavitation becomes less energetic. Experiments are needed to check the validity of this model, however, and for the present we consider the entire zone as hazardous without attempting to estimate a variable kill probability. The depth of the damage zone, V , may also be in error, since we do not know how the tension wave propagates downward below the cavitated region. This, too, must be determined from experiments. These uncertainties notwithstanding, this simple representation of the remote damage zone provides a convenient and meaningful method of comparing the probable effects of different explosive charges.

6.2.2 From contours (such as Figure 6) generated by the Gaspin-Price computer program, values of V and H were determined for a number of charge weights and depths. These results are most conveniently summarized by plotting V and H vs charge depth for a particular charge weight. Three such plots are shown in Figures 8, 9, and 10 for 1-, 10-, and 100-lb charges, respectively. In each figure the solid line shows the horizontal dimension, H , which is read from the left-hand ordinate scale, and the dashed line shows V which is read from the right-hand ordinate. As the depth of the charge increases H first increases steeply, then increases more gradually until it passes through a broad maximum and decreases to zero at some considerable depth. The thickness of the layer, V , is greatest for a shallow charge and decreases continuously as charge depth increases. Theoretically, both curves should pass through zero for a surface burst (charge depth = 0) and again for some maximum charge depth.

6.2.3 The effect of changing charge weight while the depth is held constant can be found by interpolating between the curves for constant charge weight. Such an interpolation is illustrated for a 100-ft burst depth in Figure 11, with a logarithmic ordinate scale for charge weight and linear scales for V and H . For charge weights outside the range of those shown here, boundaries of the cavitation zone can be quickly found using the computer program given in Appendix A of Gaspin and Price (1972).

6.3 Approximation Formulas for Shallow Charges

6.3.1 The above curves are poorly defined for shallow charge depths, where dimensions change rapidly. It turns out that for charge depths no greater than about fifty feet, however, the quantities H and V can be approximated by simple formulas which can be used for charge weights of up to 1000 lbs.

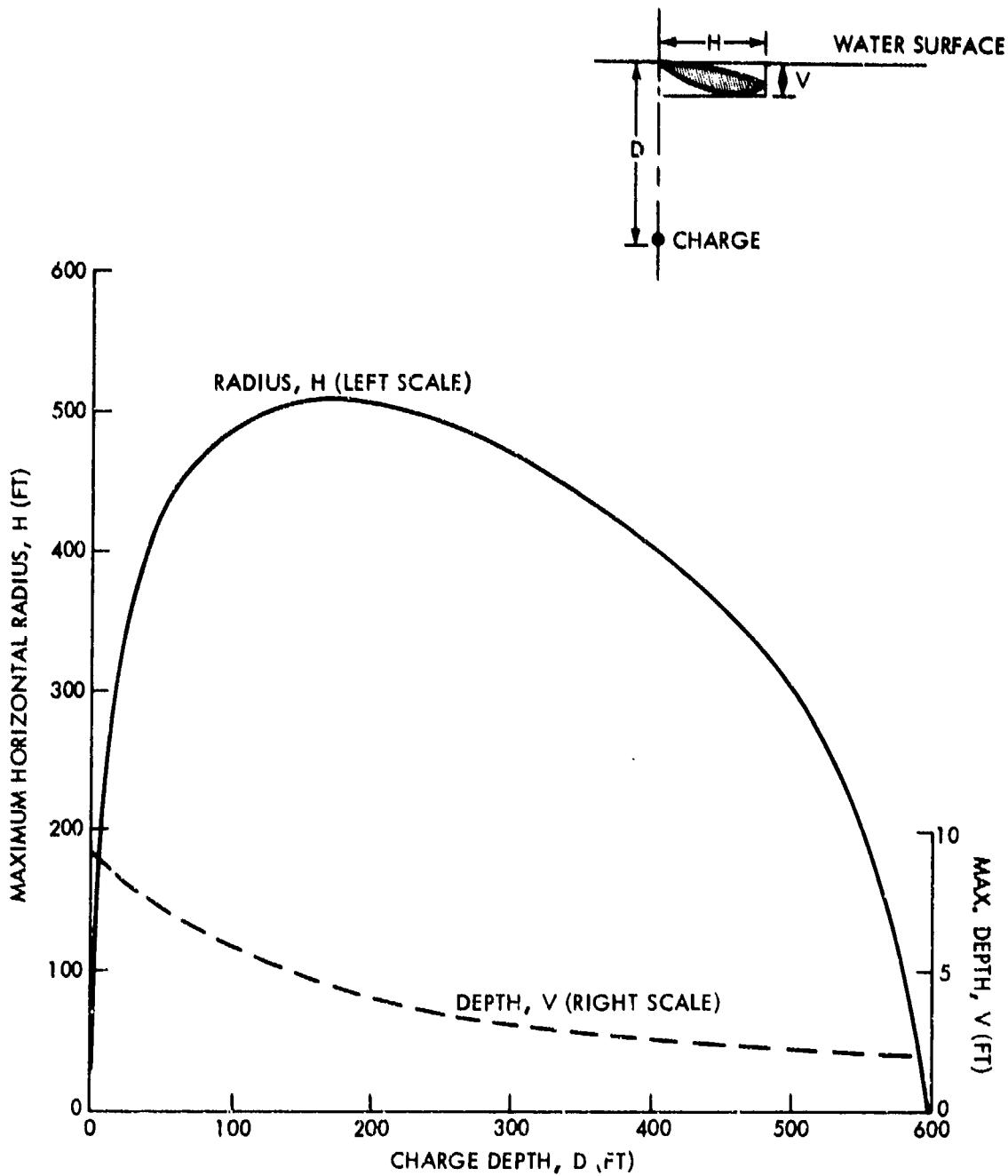


FIG. 8 THEORETICAL REMOTE LETHAL ZONE BOUNDARIES FOR 1-LB CHARGE AT VARIOUS DEPTHS

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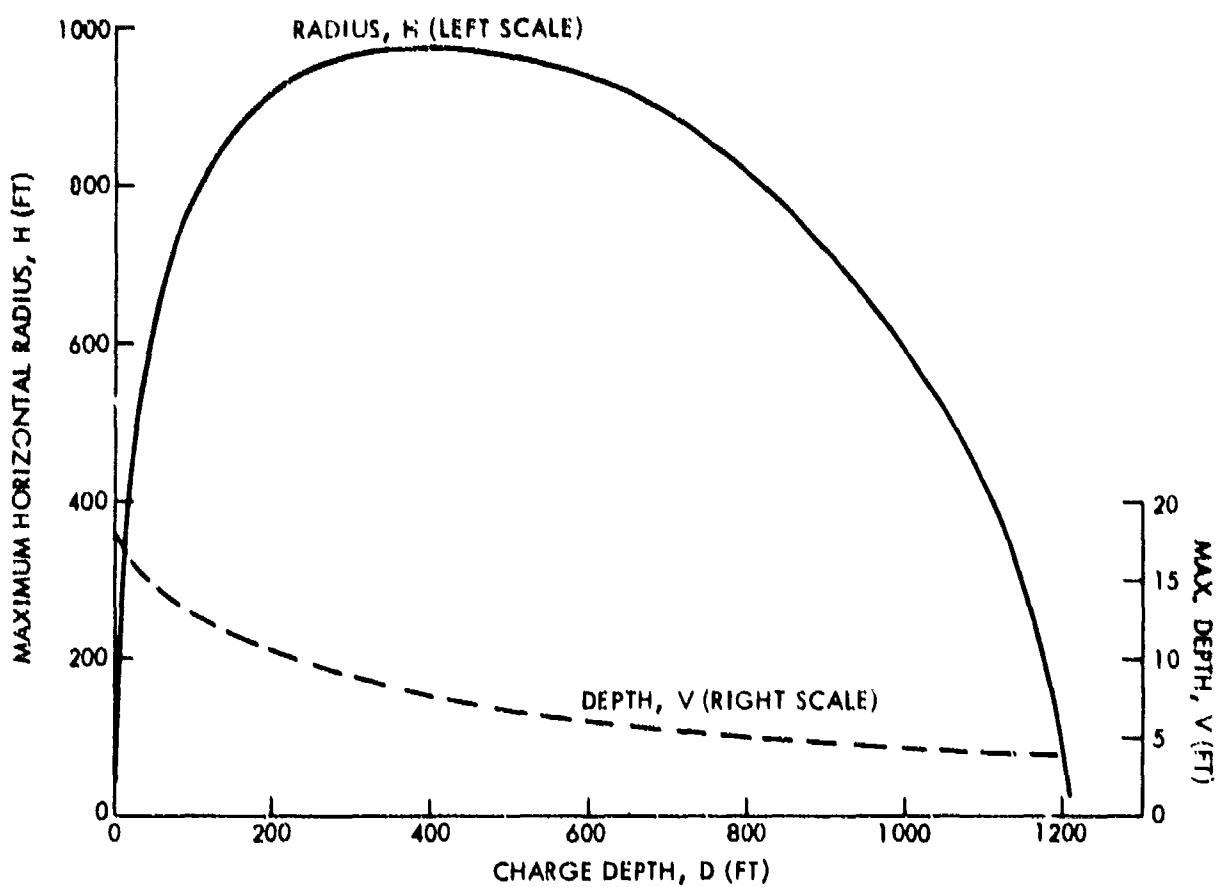
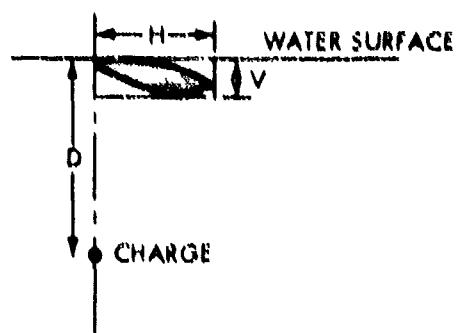


FIG. 9 THEORETICAL REMOTE LETHAL ZONE BOUNDARIES FOR 10-LB CHARGE AT VARIOUS DEPTHS

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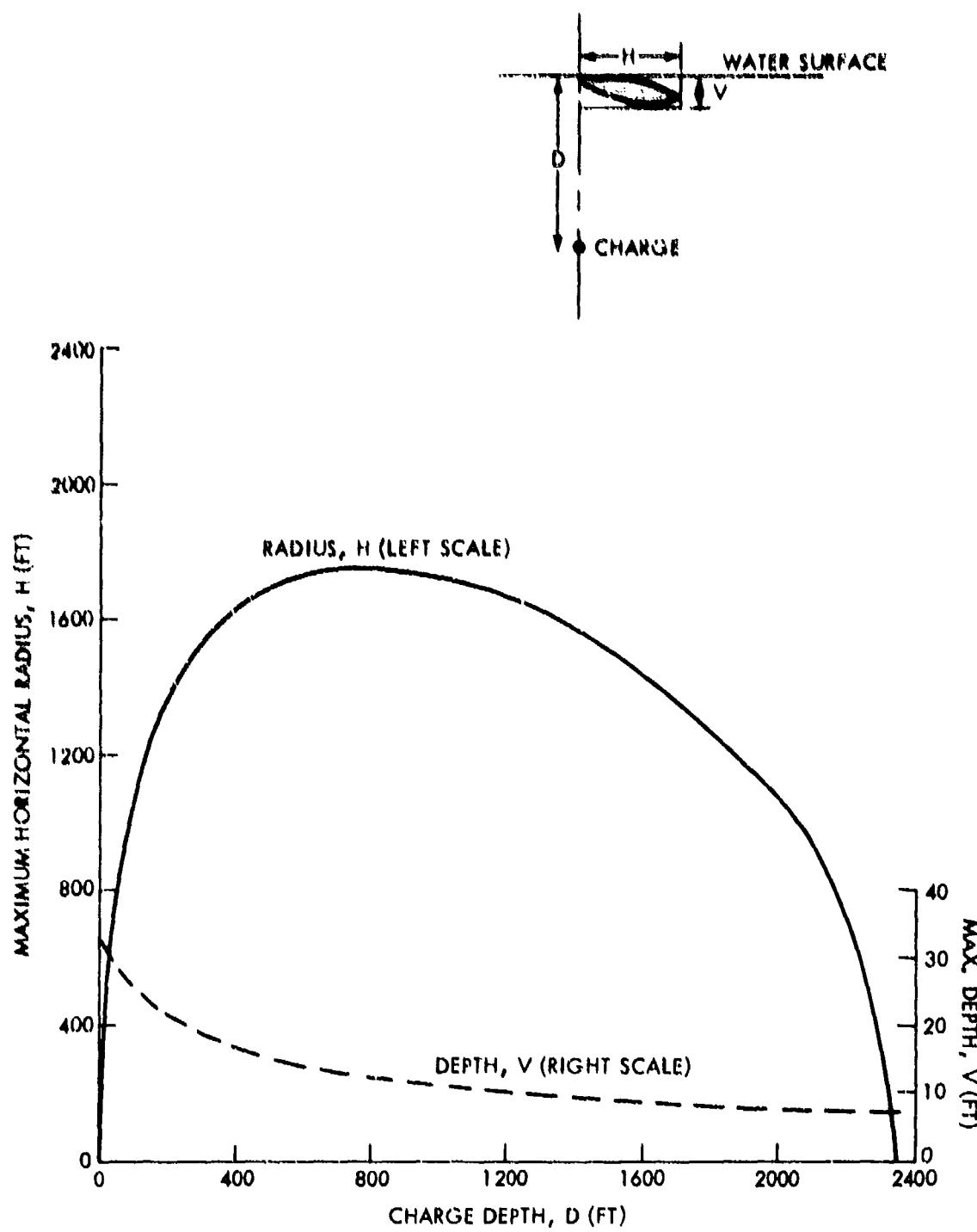


FIG. 10 THEORETICAL REMOTE LETHAL ZONE BOUNDARIES FOR 100-LB CHARGE AT VARIOUS DEPTHS

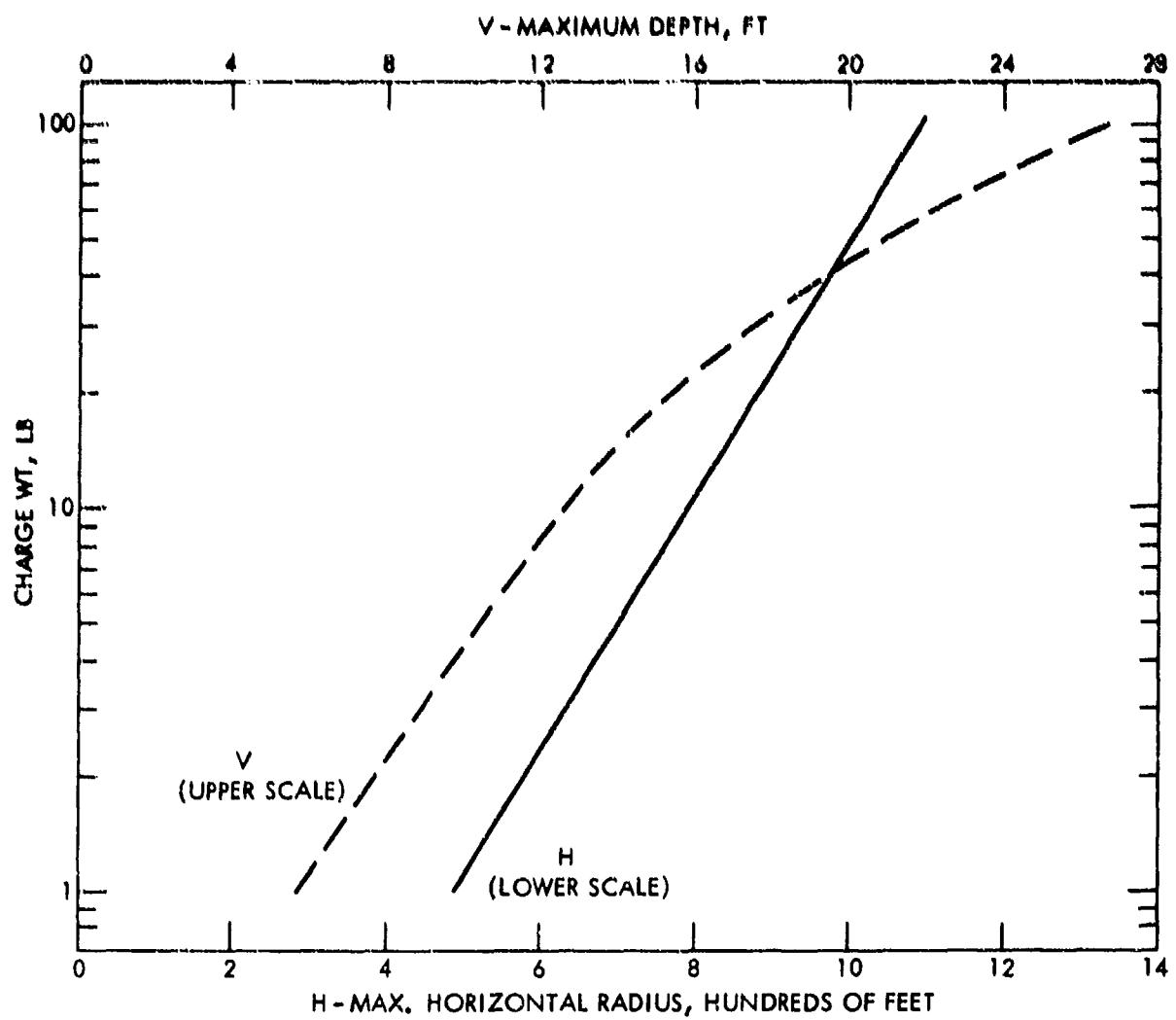


FIG. 11 THEORETICAL REMOTE LETHAL ZONE BOUNDARIES FOR CHARGES
AT 100-FT DEPTH

FOR $W < 1000$ LBS, $D < 50$ FT

$$H \approx X + W^a \quad (6)$$

where

$$X = 70 \sqrt{D} \quad (7)$$

$$a = 0.02 \sqrt{D}, \quad (8)$$

$$\text{and } V \approx 8 W^{0.3} \quad (9)$$

In other words, for small charges at fairly shallow depths (< 50 ft), the radius of the remote damage disc (H) is almost independent of charge weight but increases as the square root of the charge depth; the vertical extent of the zone (V) does not vary with charge depth but increases with increasing charge weight, roughly as the cube root of the weight*.

6.3.2 Interestingly enough, Lavergne (1970) not only cites the lethal radius reproduced here as Equation (1), but also discusses the implications of bulk cavitation in the fish-kill problem. He does not, however, suggest directly equating the two as we have done here, and, at first glance, seems to have arrived at some conclusions different from those derived here. For example, Lavergne (1970) states "....it is clear that strong charges shot at the surface will cause much more damage than equivalent charges shot at depth". This comment is in agreement with our results (Figures 8-10) only for very specific choices of "deep" and "shallow" depths; for many other conditions, e.g., those represented by Equations 6-9 above, we would conclude that the "deeper" charge was more damaging than the "shallow" one. Here we have an example of the difficulties one faces in trying to make simple generalizations about the damage problem.

VII. COMPARISONS FOR SELECTED CHARGE CONFIGURATIONS

7.1 General

7.1.1 Damage ranges derived from the new prediction scheme described above have been compared with those of three earlier publications: Aplin (1947), CBL (1948), and CEQ (1970). From Aplin (1947) and CBL (1948) we have actual measurements of explosion effects on caged fish. Although their tests were in shallow water and, hence, not fully comparable with our pressure-field model, our damage predictions are in reasonably good agreement with the experimental results. From CEQ (1970) we have simply an estimate of the range out to which a very large explosion will probably kill swimbladder fish. Our prediction method indicates far less devastation from such a charge.

7.2 Comparison with Aplin (1947)

7.2.1 In his limited series of measurements, Aplin (1947) apparently moved a cage containing several fish closer and closer to repeated explosions until

* Equations 6-9 probably overestimate the size of the remote damage zone for very large charges at shallow depths. For such charge configurations there is a so-called "anomalous surface cutoff region" near the surface, within which the wave forms differ from those assumed here.

he found the range at which that particular charge weight (either 20-lb or 40-lb) was lethal. The cage was suspended just below the water surface and the charge depth was always 4 feet. The water depth was apparently about 55 feet, since one test was reported in which the cage was at that depth "on the bottom directly below the charge". His target specimens included a number of fish that do not have swimbladders, and these were not harmed although swimbladder fish in the same cages were killed.

7.2.2 Aplin's observations are shown in Figure 12 along with shaded areas which indicate the damage zones predicted by the present study. Since the charges were at shallow depth, the dimensions of the shaded areas were obtained from Equations (6) - (9) above.

7.2.3 With the 40-lb charge, Figure 12a, small (1/2-lb) fish were killed at a greater range than our method predicts, while larger fish (2-lb) survived until they were placed well within the predicted damage zone. This may be evidence that small fish are more vulnerable to cavitation damage than larger ones. Another possible explanation is the effect of secondary shocks caused by reflection of the explosion wave off the bottom. Our new damage model does not take bottom reflections into account, and they may seriously complicate the damage field in shallow water.

7.2.4 With the 20-lb charge, Figure 12b, the observed lethal range is again well within the predicted damage zone. It is unfortunate for our purposes that no swimbladder fish were included in the deep cage shown on the bottom, below the charge. Had there been, we would have had a most valuable checkpoint for the prediction model.

7.3 Comparison with CBL (1948)

7.3.1 The CBL (1948) tests were an extensive and very well-documented series of experiments in which numerous caged swimbladder fish were placed at a number of distances from 30-lb and 300-lb charges. The charges and fish cages were apparently suspended at about 15-ft depth in shallow water (at least 25 ft and no more than 40 ft deep). Thus, we have a very complicated pressure field of interacting surface and bottom reflections. Although no pressure-time recordings of the explosion wave were made during the tests, the fish-kill data themselves give some indication of the ranges at which the reflected-wave interactions probably become dominant in the damage effects.

7.3.2 Results of the CBL (1948) tests are summarized in Figure 13; data for 30-lb charges and 300-lb charges are shown at the top (Figure 13a) and bottom (Figure 13b), respectively. At the fish cage locations indicated by solid points, the percent fatalities* are shown above the symbol and the sample size is shown in parentheses below the symbol. Again, the shaded areas indicate our predicted damage zones (Equations 6-9) for the same charges fired in deep water, i.e., for pressure fields not complicated by bottom reflections.

7.3.3 With the 30-lb charges, Figure 13a, the percent fatalities decreased steadily with increasing range until there were no fatalities at 350 ft from the charge. Continuing on out to greater ranges we see damage increasing again

* "Fatalities" include both fish that were killed outright and those that were injured so severely that they would not be expected to survive.

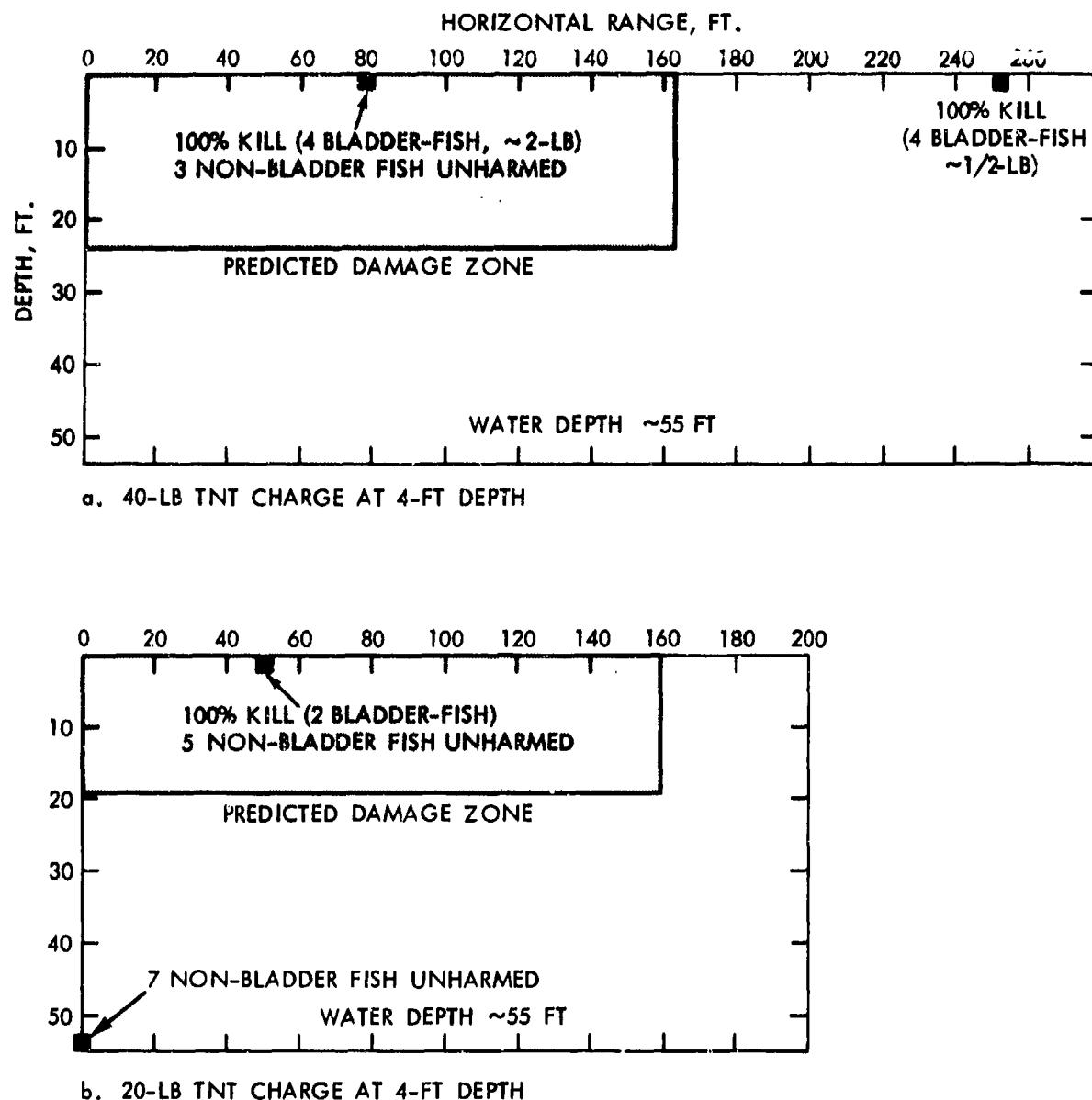
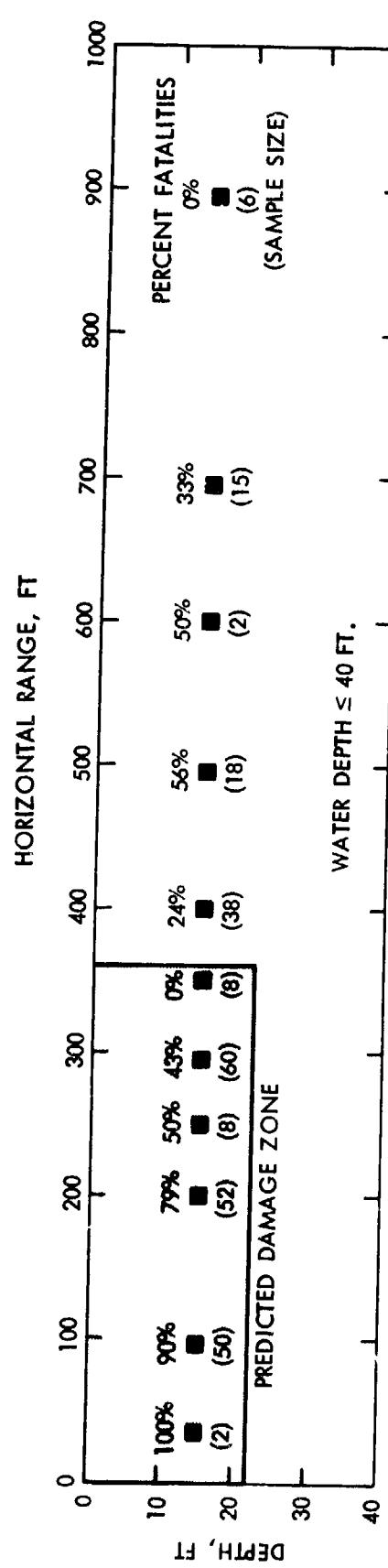
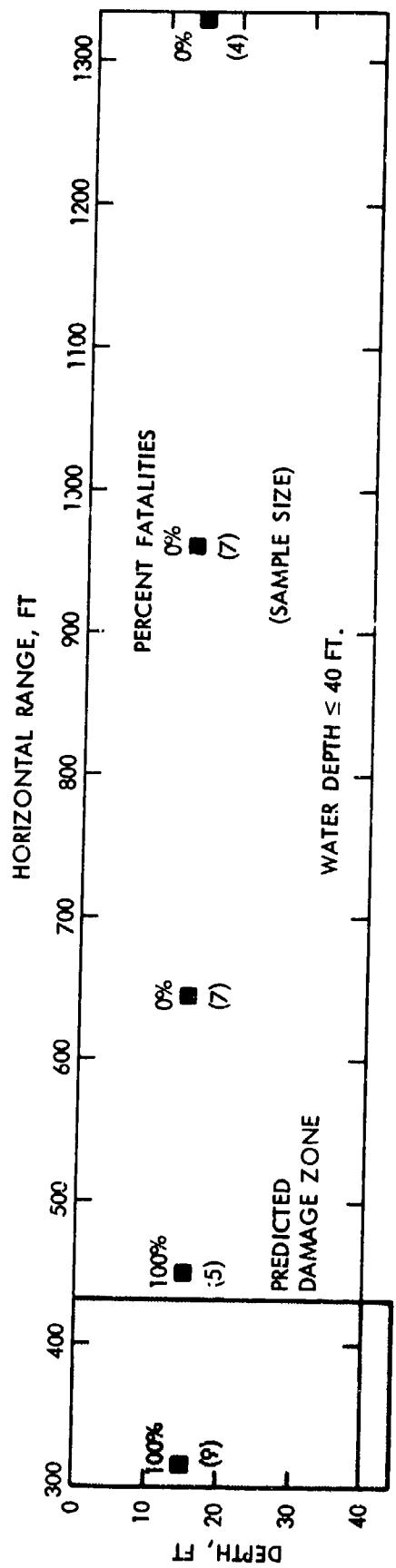


FIG. 12 COMPARISON OF DATA FROM APLIN (1947) WITH PREDICTED REMOTE DAMAGE ZONES FOR SWIMBLADDER FISH IN DEEP WATER.



a. 30-LB CHARGE AT 15 FT DEPTH



b. 300-LB CHARGE AT 15 FT DEPTH

FIG. 13 COMPARISON OF DATA FROM CBL (1948) WITH PREDICTED REMOTE DAMAGE ZONES FOR SWIMBLADDER FISH IN DEEP WATER.

and going through a maximum at about 500-600 ft range. As the authors of CBL (1948) point out, this reversing pattern of damage with increasing range undoubtedly signifies the introduction of new pressure-field characteristics, and it is not meaningful to compare our prediction with these furthest out results. If we look at just the closer-in sequence of measurements, however, there is gratifying (and probably somewhat fortuitous) agreement with our damage model.

7.3.4 The 300-lb charge data, Figure 13b, define only 100% or 0% fatality locations. Here, also, the extent of our predicted damage zone agrees quite well with the observations.

7.4 Comparison with CEQ (1970)

7.4.1 In its special report to the President on Ocean Dumping, the Council on Environmental Quality states that an explosion of 1000 tons of munitions "will kill most marine animals within 1 mile of the explosion and will probably kill those fish with swimbladders out to 4 miles from the explosion". This estimate of such far-reaching effects is based on the assumption of a shock wave peak pressure criterion for damage. With a different damage criterion, the predicted damage zone is drastically decreased.

7.4.2 In Figure 14 we can compare two estimates of the hazard zones for 2000 tons of explosive detonated at a depth of 3000 ft. For this configuration the damage rule applied in CEQ (1970) says that all swimbladder fish within about 5 miles would probably be killed.

7.4.3 Our prediction model says that fish-kill would occur only at two locations: very near the charge, and in the remote damage zone at the surface above the charge. Although we do not yet know the size of the near-charge damage zone, from overall consideration of the data in hand, it seems likely that it will not extend much more than 1/2 mile from the explosion. The predicted boundaries of the remote damage zone located above the charge were read from Figure 6 of Gaspin and Price (1972): a radius of 9250 ft and a depth of 250 ft, for this configuration. Thus, the model described here predicts that the hazardous area within the water column is only about 10% of the area indicated by CEQ (1970). This comparison illustrates one of the important reasons for developing a realistic prediction model.

VIII. SUMMARY

8.1 Insofar as possible, the Navy attempts to avoid, or at least minimize, fish kills when necessary underwater explosions tests are conducted. For successful control of detrimental effects we need an improved method of predicting the extent and location of the hazardous regions for various weights and depths of explosive charges. Lethal range equations available from past studies give widely varying estimates. They also fail to take into account the special character of the explosion pressure field near the water surface.

8.2 A review of the literature shows that swimbladder fish are more susceptible to tension than to compression, and that when they are at considerable range from an explosion, fish near the surface are more vulnerable than those at greater depths. The combination of these factors point to bulk cavitation as the most significant explosion phenomenon for predicting the most distant ranges at which fish may be killed.

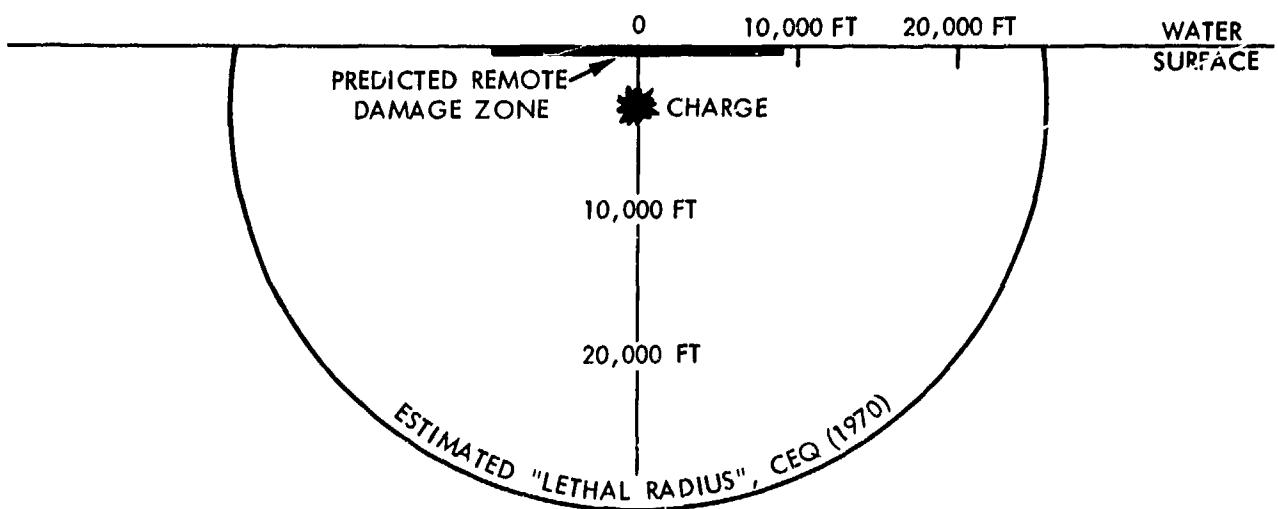


FIG. 14 COMPARISON OF PREDICTED DAMAGE RANGES FOR A 2 KILOTON TNT CHARGE DETONATED AT 3000 FT. DEPTH.

NOLTR 73-103

8.3 It is proposed that the zone of bulk cavitation of the water be equated to a zone of probable fish kill, called the "remote damage zone." There is also a second danger zone, a relatively small region surrounding the charge, where all biologicals will probably be destroyed by the violence of the explosion. This second zone, called the "immediate kill zone" probably contributes only a minor fraction of fish-kill from most explosions.

8.4 The remote damage zone is approximated by a large, thin disc-shaped layer of water that lies at the surface and is centered above the charge. The dimensions of this zone for various charge weights and depths are predicted from the bulk cavitation theory of Gaspin and Price (1972).

8.5 Predicted results appear to be in reasonable agreement with available experimental results, but the limited fish-kill data do not permit a true test of the model. At the least, however, the damage zone prediction method proposed here is in better agreement with experimental observations than prediction rules that were previously suggested. Until new data are obtained from controlled experiments, we believe that this new model gives the most realistic estimates of explosion effects on swimbladder fish that can be made at this time.

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APPENDIX A

DATA OF HUBBS AND RECHNITZER (1952)

1. The experiments of Hubbs and Rechnitzer (1952) provided valuable information for the study reported here. Since the explosion pressure fields for these tests were highly specialized, the results are not directly comparable to the experimental conditions discussed in the body of the report. Several important conclusions that are stated or that can be derived from re-examination of the data are in agreement with the present study, however, as shown in the following discussion.

2. In brief, the experiments involved exposing a number of fish, suspended in an array of cages, to the shock waves generated by explosive charges "jetted" into the bottom. Most of the explosive charges were buried below the ocean floor at depths of up to 65 ft, by means of a water jet. The experiments were designed to compare the effects of two types of explosive materials, dynamite and black powder, so most of the data-gathering effort was concentrated on the biological results. Measurements of the explosion pressure field were scanty. Peak pressures were reported for some of the fish-cage locations, but no pressure-time histories were shown for the peculiar waveforms that would have been generated in the water by the "jetted" charges. Thus, peak pressure alone had to serve as a reference base for describing the explosion parameters. And a considerable amount of smoothing and extrapolation was applied in the course of the present study before even this parameter could be used in arriving at some of the following judgements.

3. For purposes of our study, the most significant results reported by Hubbs and Rechnitzer are as follows:

3.1 The entire pressure wave, not just the peak pressure, determines the explosion damage to fish. Black powder and dynamite charges produced radically different types of explosion pressure waves in the water, although the peak pressures were similar for the two materials. Black powder charges killed very few fish, while dynamite charges were lethal more often than not. The dynamite pressure wave was similar to the "typical" explosion shock waves described in the body of the report. In contrast to the steep-fronted, sharply cut-off dynamite shocks, the black powder pressure wave was nearly sinusoidal; the pressure change was relatively slow and it took several milliseconds for the pressure level to rise to its smoothly-rounded peak, and a like amount of time for it to decay back to ambient. The pressure gradients in the dynamite wave were much larger than those in the black powder wave. The negative pressures caused by surface reflections were probably also much greater for the dynamite than for the black powder wave. We cannot judge whether the difference in gradients, the difference in negative pressure, or some combination of these two, is the primary reason for the differences in lethality.

3.2 Fish near the water surface are more vulnerable to explosions than fish at considerable depths. We sorted the extensive fish-damage data for dynamite

charges into "near-surface" and "near-bottom" groupings, and compared peak pressures (some were reported, some we estimated) with percent fatalities in each of the groups. For each set (i.e., "near-surface" or "near-bottom" fish) there is a surprisingly narrow range of pressures within which the percent fatalities rises abruptly from 0% to 100%. This critical pressure is in the neighborhood of 50 psi for the "near-surface" fish, and 120 psi for the "near-bottom" fish. Here we have the same kinds of fish being exposed to the same kinds of pressure waves, and find the greater damage being caused by the less severe shock. The "near-surface" fish are undoubtedly in the zone of bulk cavitation (for the reflection of a 50 psi compression wave at the surface would surely set up cavitation in the water) whereas the "near-bottom" fish probably are below the hazardous zone.

3.2.1 One particular set of test results (Shot No. 3) provides a good demonstration of the important part that location in the water column plays in the damage picture. In this case a 10-lb dynamite charge was jetted 55 ft below the bottom in a water depth of 30 ft. Three fish cages were placed on the bottom very near the charge "jet-hole" and seven more cages were placed vertically above these, three about 6 ft above the bottom, three about 11 ft up, and one at the surface. The fish in all the cages were anchovies. The total fatalities at the different depths were as follows: 100% at the surface; 100% at 19 ft; 80% at 25 ft; and 33% just off the bottom at 30 ft.

4. In their discussion of the conspicuous decrease of fatalities with increasing depth of the fish, Hubbs and Rechnitzer suggest that the deeper cages might have been shielded from the effects of the jetted charges by the bottom, or that the explosion energy might have been focussed towards the surface by the special charge configurations. This does not seem likely, however, from our evaluation of the pressure values reported at various locations. We believe that the explanation probably lies in the cavitation phenomenon discussed in the body of the report.